

Modeling SN 1996cr's X-ray lines at high-resolution: *Sleuthing the ejecta/CSM geometry*

Daniel Dewey*, Franz E. Bauer[†] and Vikram V. Dwarkadas**

*MIT Kavli Institute for Astrophysics and Space Research, Cambridge, MA 02139, USA

[†]Dept. de Astronomía y Astrofísica, Pontificia U. Católica de Chile, Casilla 306, Santiago 22, Chile

**Dept. of Astronomy and Astrophysics, U. of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA

Abstract. SN 1996cr, located in the Circinus Galaxy (3.7 Mpc, $z \sim 0.001$) was non-detected in X-rays at ~ 1000 days yet brightened to $L_x \sim 4 \times 10^{39}$ erg/s (0.5-8 keV) after 10 years (Bauer et al. 2008). A 1-D hydrodynamic model of the ejecta-CSM interaction produces good agreement with the measured X-ray light curves and spectra at multiple epochs. We conclude that the progenitor of SN 1996cr could have been a massive star, $M > 30 M_\odot$, which went from an RSG to a brief W-R phase before exploding within its $r \sim 0.04$ pc wind-blown shell (Dwarkadas et al. 2010). Further analysis of the deep *Chandra* HETG observations allows line-shape fitting of a handful of bright Si and Fe lines in the spectrum. The line shapes are well fit by axisymmetric emission models with an axis orientation ~ 55 degrees to our line-of-sight. In the deep 2009 epoch the higher ionization Fe XXVI emission is constrained to high latitudes: the Occam-est way to get the Fe H-like emission coming from high latitude/polar regions is to have more CSM at/around the poles than at mid and lower latitudes, along with a symmetric ejecta explosion/distribution. Similar CSM/ejecta characterization may be possible for other SNe and, with higher-throughput X-ray observations, for gamma-ray burst remnants as well.

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INTRODUCTION TO SN 1996CR

SN 1996cr, located comparatively nearby in the Circinus Galaxy (3.7 Mpc, $z \sim 0.001$) was serendipitously detected as a ULX at an age of ~ 5 years [1]. As detailed in Bauer et al. [2]: i) followup archival research and VLT observations (at age ~ 10 years) allowed SN 1996cr to be classified as a Type IIIn SNe, and ii) archival X-ray data showed that it was not detected at an age of ~ 1000 days, yet brightened to $L_x \sim 4 \times 10^{39}$ erg/s (0.5-8 keV) after 10 years. This X-ray behavior is shared only with SN 1987A, and is roughly shown in Figure 1 in the context of other X-ray-detected SNe and core-collapse (CC) SNRs. Because of this behavior, and given an indication of Doppler structure in 2004 *Chandra* HETG data, we proposed and obtained a deep, 485 ks HETG observation (PI Bauer) near the beginning of 2009. In large part because of the high quality of this recent data we were able to tune a 1-D hydrodynamic model to agree with the *multi-epoch* X-ray data (next section), and we are now investigating signatures of the ejecta/CSM geometry in the HETG line shapes (last section.)

HYDRODYNAMIC MODEL AND X-RAY EMISSION

A 1-D (spherical) hydrodynamic model of the ejecta-CSM interaction is developed in Dwarkadas et al. [4]; post-processing calculates the X-ray emission from the non-radiative shocks, showing good agreement with the measured X-ray light curve and spectra at multiple epochs. Given our inferred configuration, Figure 2, a realistic evolutionary scenario for SN 1996cr's progenitor has it evolving from the RSG to the W-R stage, creating a wind-blown bubble with a dense shell at about 0.04 pc, and then exploding as a SN. Some conclusions from the modeling are that:

- The 1-D model explains the majority of the observed X-ray continuum and lines, and their variation in time.
- The velocities of plasma in the model agree with the scale of the line broadening seen in the HETG data.
- The inner ejecta core is opaque to HETG X-rays as late as 2009 when it has a plateau density of 10^5 amu cm $^{-3}$ and a radius of 0.065 pc, giving a column density along the diameter of 4.0×10^{22} amu cm $^{-2}$ of high-Z material.

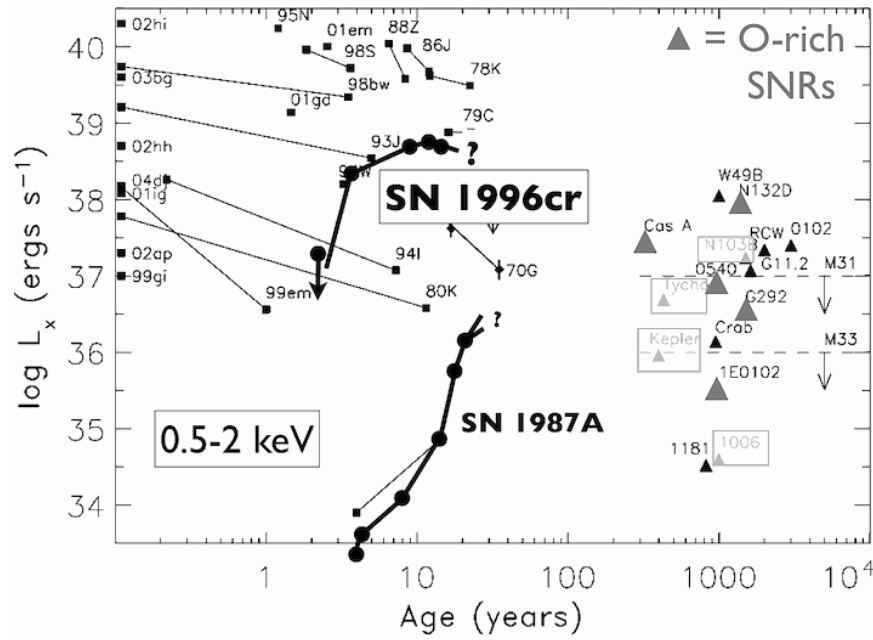


FIGURE 1. The unique behavior of SN 1996cr and SN 1987A. Their X-ray light curves are overplotted on an L_X vs Age plot from Immler & Kuntz [3]. Unlike other X-ray-bright SNe, these two show a dramatic (re-)brightening at ages of a few years to decades. As these and other SNe age we will begin to fill in the CC SNe-SNR gap seen between ages of 30 to 300 years.

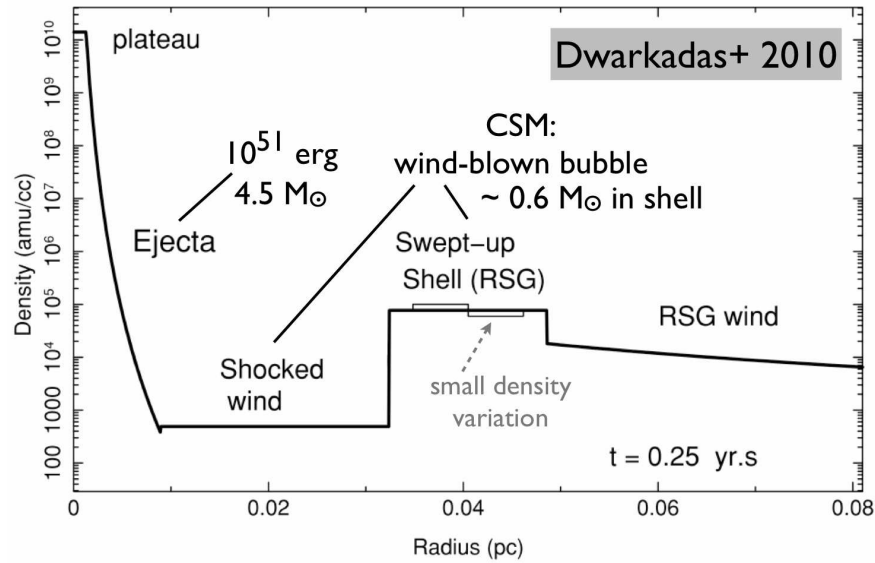


FIGURE 2. Initial density profile for the hydrodynamic model of SN 1996cr. Several months after the SN explosion the ejecta (near the origin at left) is seen making its way into the low density W-R wind cavity while the shell of swept-up RSG wind material doesn't know what's going to hit it. See Figure 3 of Dwarkadas et al. [4] for snapshots of the further evolution of the hydrodynamics beyond this initial configuration.

- Initially the flux from the forward-shocked shell dominates. However, at ~ 8 years the reverse-shocked ejecta contributes 50% of the flux, this fraction grows to $\sim 70\%$ at 15–20 years.
- Some small fraction (by mass/volume) of denser CSM is needed to produce some low-ionization lines seen in the X-ray spectrum; this “clump” emission is a small perturbation on the main hydrodynamics.

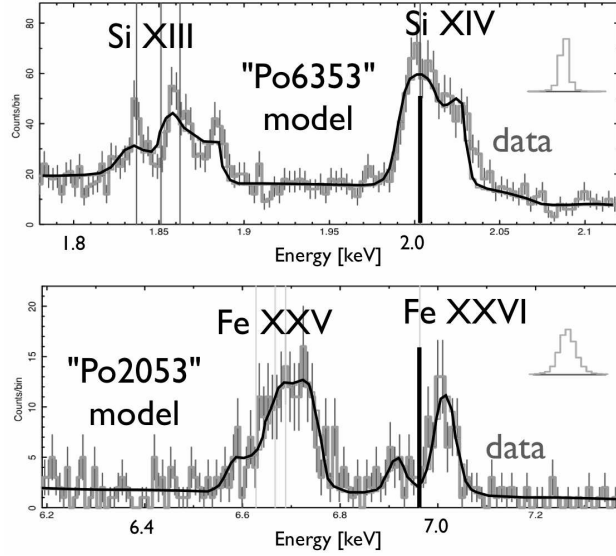


FIGURE 3. Line shapes of the bright Si and Fe-K lines in SN 1996cr. Lines of Si (top) and Fe (bottom) show Doppler-modified structure with velocity components of several thousand km/s; the HETG instrumental profile is shown in the upper right. Note the very different shapes of the H-like Si XIV and Fe XXVI lines with respect to their nominal line energies (vertical black lines.) The solid black curves are model fits based on our 1-D hydrodynamic model velocities and an emission region that does not cover a full sphere, see Figures 4 & 5.

CHANDRA / HETG LINE SHAPES AND EJECTA-CSM GEOMETRY

With a general hydrodynamic picture established, we are now looking at detailed line-shape fitting of a handful of the lines, in particular Si and Fe-K lines shown in Figure 3. Using simple 3-D modeling techniques [5] we compared the HETG data with the line shapes expected from our 1-D model (with spherical symmetry and an opaque core) and found that, while there is qualitative agreement, there are statistically significant departures from this simple model. Since the SNe is unresolved in the X-ray (and only just resolved by VLBI in 2007 [2]) we explore simple, plausible geometric modifications that can better fit the line shapes.

One option is to retain the 1-D radial solution (i.e., densities and velocities), but to restrict the interaction and emission to less than the full 4π solid angle; examples of such geometries are shown in Figure 4. In reality, this approximation could be appropriate if either the CSM is non-uniform or if the explosion/ejecta is not spherically symmetric. Of course this truncation of the solid angle also reduces the model flux, but a flux factor of up to a few can be accommodated with small changes to the parameters (density, radii) and still obtain light curve and spectral agreement.

Comparing models with data in Figures 3 & 5, we find that the line shapes are well fit by “polar” models consisting of uniform emission within a half-opening angle of the poles: within ~ 60 – 70 degrees for Si and other lines and within ~ 10 – 30 degrees for the Fe XXVI line. In all cases the polar axis is consistent with being oriented at ~ 50 – 60 degrees to our line-of-sight; this leads to the schematic image shown in Figure 5 (the position angle is arbitrary.)

A preliminary sensitivity study of the effects of changing the hydrodynamic parameters suggests that the easiest way to get more Fe XXVI emission is to increase the swept up mass at high latitudes, rather than, say, changing the ejecta mass or energy along that direction. We are currently in the processes of creating a more realistic model to take this and the optical line shapes into account. Perhaps in the future similar CSM/ejecta sleuthing will be possible for more SNe and even gamma-ray burst remnants.

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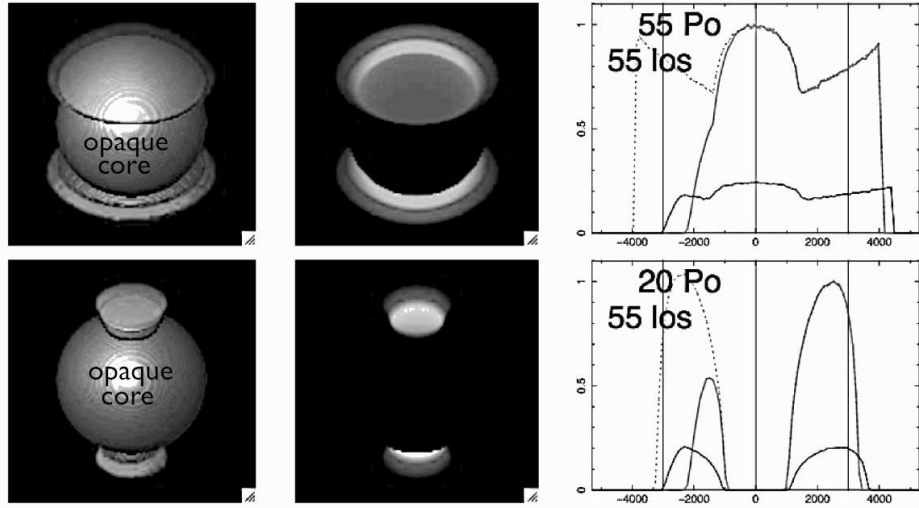


FIGURE 4. From geometry to line shape. We calculate the line shape from emission that is confined within a range of the pole, e.g., within 55 degrees (upper row) and within 20 degrees (lower row.) Including an opaque core and viewing the system at an angle to the line-of-sight, here 55 degrees, produces a variety of possible line shapes (right plots.) The middle images would be seen by a high spatial-resolution X-ray telescope.

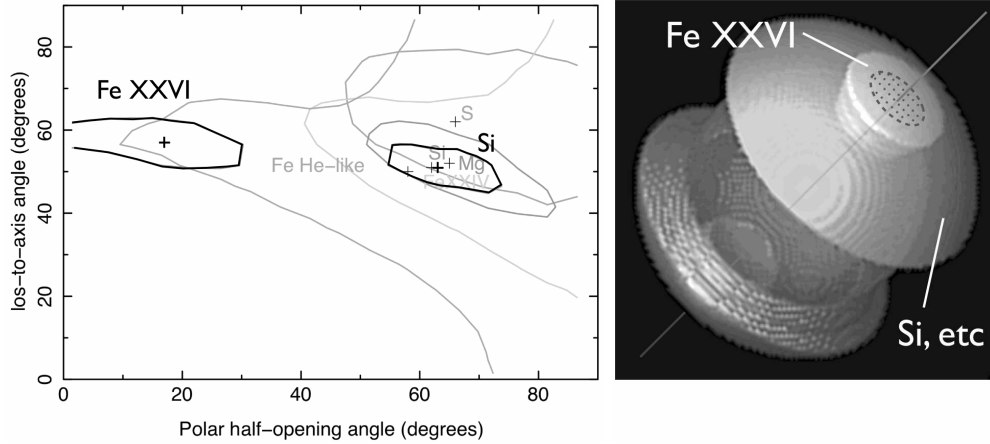


FIGURE 5. Fitting the emission-line geometries. Using line shapes specified by a polar angle and the angle to the line-of-sight, we generate 1-sigma confidence contours for fits to discrete lines, left. The Si, S, Mg, and the lower-ionization Fe XXIV lines are all fit with similar parameters. In contrast the Fe XXVI line is much better fit with its emission confined to higher-latitudes. The solid black lines in Figure 3 show the Si and Fe fits; the image at right is the implied geometry.

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